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Net–Charge Fluctuations in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV

(The ALICE Collaboration)

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Baltasar Dos Santos Pedrosa,[6] J. Bán,[41] R.C. Baral,[42] R. Barbera,[43] F. Barile,[22] G.G. Barnaföldi,[7] L.S. Barnby,[44] V. Barret,[39] J. Bartke,[45] M. Basile,[8] N. Bastid,[39] S. Basu,[10] B. Bathen,[28] G. Batigne,[32] B. Batyunya,[46] C. Baumann,[33] I.G. Bearden,[47] H. Beck,[33] N. Behera,[48] I. Belikov,[49] F. Bellini,[8] R. Bellwied,[50] E. Belmont-Moreno,[9] G. Bencedi,[7] S. Beole,[51] I. Berceanu,[25] A. Bercuci,[25] Y. Berdnikov,[52] D. Berenyi,[7] A.A.E. Bergognon,[32] D. Berzano,[16] L. Betev,[6] A. Bhasin,[53] A.K. Bhati,[5] J. Bhom,[54] N. Bianchi,[55] L. Bianchi,[51] C. Bianchin,[56] J. Bielčík,[2] J. Bielčíková,[3] A. Bilandzic,[57,47] S. Bjelogrlic,[58] F. Blanco,[50] F. Blanco,[59] D. Blau,[15] C. Blume,[33] M. Boccioli,[6] N. Bock,[29] S. Böttger,[60] A. Bogdanov,[61] H. Bøggild,[47] M. Bogolyubsky,[62] L. Boldizsár,[7] M. Bombara,[63] J. Book,[33] H. Borel,[40] A. Borissov,[64] S. Bose,[65] F. Bossú,[51] M. Botje,[57] B. Boyer,[66] E. Braidot,[67] P. Braun-Munzinger,[26] M. Bregant,[32] T. Breitner,[60] T.A. Browning,[68] M. Broz,[69] R. Brun,[6] E. Bruna,[51,16] G.E. Bruno,[22] D. Budnikov,[70] H. Buesching,[33] S. Bufalino,[51,16] O. Busch,[27] Z. Buthelezi,[71] D. Caballero Orduna,[4] D. Caffarri,[56] X. Cai,[72] H. Caines,[4] E. Calvo Villar,[73] P. Camerini,[74] V. Canoa Roman,[75] G. Cara Romeo,[17] F. Carena,[6] W. Carena,[6] N. Carlin Filho,[76] F. Carminati,[6] A. Casanova Díaz,[55] J. Castillo Castellanos,[40] J.F. Castillo Hernandez,[26] E.A.R. Casula,[77] V. Catanescu,[25] C. Cavicchioli,[6] C. Ceballos Sanchez,[78] J. Cepila,[2] P. Cerello,[16] B. Chang,[37,79] S. Chapeland,[6] J.L. Charvet,[40] S. Chattopadhyay,[10] S. Chattopadhyay,[65] I. Chawla,[5] M. Cherney,[80] C. Cheshkov,[6,81] B. Cheynis,[81] V. Chibante Barroso,[6] D.D. Chinellato,[82] P. Chochula,[6] M. Chojnacki,[58] S. Choudhury,[10] P. Christakoglou,[57] C.H. Christensen,[47] P. Christiansen,[83] T. Chujo,[54] S.U. Chung,[84] C. Cicalo,[85] L. Cifarelli,[8,6,18] F. Cindolo,[17] J. Cleymans,[71] F. Coccetti,[18] F. Colamaria,[22] D. Colella,[22] G. Conesa Balbastre,[34] Z. Conesa del Valle,[6] P. Constantin,[27] G. Contin,[74] J.G. Contreras,[75] T.M. Cormier,[64] Y. Corrales Morales,[51] P. Cortese,[86] I. Cortés Maldonado,[87] M.R. Cosentino,[67] F. Costa,[6] M.E. Cotallo,[59] E. Crescio,[75] P. Crochet,[39] E. Cruz Alaniz,[9] E. Cuautle,[88] L. Cunqueiro,[55] A. Dainese,[56,31] H.H. Dalsgaard,[47] A. Danu,[89] D. Das,[65] K. Das,[65] I. Das,[66] A. Dash,[82] S. Dash,[48] S. De,[10] G.O.V. de Barros,[76] A. De Caro,[90,18] G. de Cataldo,[91] J. de Cuveland,[21] A. De Falco,[77] D. De Gruttola,[90] H. Delagrange,[32] A. Deloff,[92] V. Demanov,[70] N. De Marco,[16] E. Dénes,[7] S. De Pasquale,[90] A. Deppman,[76] G. D Erasmo,[22] R. de Rooij,[58] M.A. Diaz Corchero,[59] D. Di Bari,[22] T. Dietel,[28] S. Di Liberto,[93] A. Di Mauro,[6] P. Di Nezza,[55] R. Divià,[6] Ø. Djuvsland,[23] A. Dobrin,[64,83] T. Dobrowolski,[92] I. Domínguez,[88] B. Dönigus,[26] O. Dordic,[94] O. Driga,[32] A.K. Dubey,[10] A. Dubla,[58] L. Ducroux,[81] P. Dupieux,[39] A.K. Dutta Majumdar,[65] M.R. Dutta Majumdar,[10] D. Elia,[91] D. Emschermann,[28] H. Engel,[60] B. Erazmus,[32] H.A. Erdal,[20] B. Espagnon,[66] M. Estienne,[32] S. Esumi,[54] D. Evans,[44] G. Eyyubova,[94] D. Fabris,[56,31] J. Faivre,[34] D. Falchieri,[8] A. Fantoni,[55] M. Fasel,[26] R. Fearick,[71] A. Fedunov,[46] D. Fehlker,[23] L. Feldkamp,[28] D. Felea,[89] B. Fenton-Olsen,[67] G. Feofilov,[24] A. Fernández Téllez,[87] R. Ferretti,[86] A. Ferretti,[51] A. Festanti,[56] J. Figiel,[45] M.A.S. Figueredo,[76] S. Filchagin,[70] D. Finogeev,[95] F.M. Fionda,[22] E.M. Fiore,[22] M. Floris,[6] S. Foertsch,[71] P. Foka,[26] S. Fokin,[15] E. Fragiacomo,[96] A. Francescon,[6,56] U. Frankenfeld,[26] U. Fuchs,[6] C. Furget,[34] M. Fusco Girard,[90] J.J. Gaardhøje,[47] M. Gagliardi,[51] A. Gago,[73] M. Gallio,[51] D.R. Gangadharan,[29] P. Ganoti,[36] C. Garabatos,[26] E. Garcia-Solis,[97] I. Garishvili,[1] J. Gerhard,[21] M. Germain,[32] C. Geuna,[40] M. Gheata,[89,6] A. Gheata,[6] B. Ghidini,[22] P. Ghosh,[10] P. Gianotti,[55] M.R. Girard,[98] P. Giubellino,[6] E. Gladysz-Dziadus,[45] P. Glässel,[27] R. Gomez,[99] E.G. Ferreiro,[35] L.H. González-Trueba,[9] P. González-Zamora,[59] S. Gorbunov,[21] A. Goswami,[100] S. Gotovac,[101] V. Grabski,[9] L.K. Graczykowski,[98] R. Grajcarek,[27] A. Grelli,[58] C. Grigoras,[6] A. Grigoras,[6] V. Grigoriev,[61] S. Grigoryan,[46] A. Grigoryan,[102] B. Grinyov,[19] N. Grion,[96] P. Gros,[83] J.F. Grosse-Oetringhaus,[6] J.-Y. Grossiord,[81] R. Grosso,[6] F. Guber,[95] R. Guernane,[34] C. Guerra Gutierrez,[73] B. Guerzoni,[8] M. Guilbaud,[81] K. Gulbrandsen,[47] T. Gunji,[103] R. Gupta,[53] A. Gupta,[53] H. Gutbrod,[26] Ø. Haaland,[23] C. Hadjidakis,[66] M. Haiduc,[89] H. Hamagaki,[103] G. Hamar,[7] B.H. Han,[104]

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L.D. Hanratty,[44] A. Hansen,[47] Z. Harmanova,[63] J.W. Harris,[4] M. Hartig,[33] D. Hasegan,[89] D. Hatzifotiadou,[17] A. Hayrapetyan,[6,102] S.T. Heckel,[33] M. Heide,[28] H. Helstrup,[20] A. Herghelegiu,[25] G. Herrera Corral,[75] N. Herrmann,[27] B.A. Hess,[105] K.F. Hetland,[20] B. Hicks,[4] P.T. Hille,[4] B. Hippolyte,[49] T. Horaguchi,[54] Y. Hori,[103] P. Hristov,[6] I. Hřivnáčová,[66] M. Huang,[23] T.J. Humanic,[29] D.S. Hwang,[104] R. Ichou,[39] R. Ilkaev,[70] I. Ilkiv,[92] M. Inaba,[54] E. Incani,[77] G.M. Innocenti,[51] P.G. Innocenti,[6] M. Ippolitov,[15] M. Irfan,[11] C. Ivan,[26] V. Ivanov,[52] A. Ivanov,[24] M. Ivanov,[26] O. Ivanytskyi,[19] P. M. Jacobs,[67] H.J. Jang,[12] M.A. Janik,[98] R. Janik,[69] P.H.S.Y. Jayarathna,[50] S. Jena,[48] D.M. Jha,[64] R.T. Jimenez Bustamante,[88] L. Jirden,[6] P.G. Jones,[44] H. Jung,[13] A. Jusko,[44] A.B. Kaidalov,[14] V. Kakoyan,[102] S. Kalcher,[21] P. Kaliňák,[41] T. Kalliokoski,[37] A. Kalweit,[106,6] J.H. Kang,[79] V. Kaplin,[61] A. Karasu Uysal,[6,107] O. Karavichev,[95] T. Karavicheva,[95] E. Karpechev,[95] A. Kazantsev,[15] U. Kebschull,[60] R. Keidel,[108] M.M. Khan,[11] S.A. Khan,[10] P. Khan,[65] A. Khanzadeev,[52] Y. Kharlov,[62] B. Kileng,[20] D.J. Kim,[37] B. Kim,[79] S. Kim,[104] T. Kim,[79] S.H. Kim,[13] M. Kim,[79] M.Kim,[13] J.S. Kim,[13] J.H. Kim,[104] D.W. Kim,[13] S. Kirsch,[21] I. Kisel,[21] S. Kiselev,[14] A. Kisiel,[98] J.L. Klay,[109] J. Klein,[27] C. Klein-Bösing,[28] M. Kliemant,[33] A. Kluge,[6] M.L. Knichel,[26] A.G. Knospe,[110] K. Koch,[27] M.K. Köhler,[26] T. Kollegger,[21] A. Kolojvari,[24] V. Kondratiev,[24] N. Kondratyeva,[61] A. Konevskikh,[95] A. Korneev,[70] R. Kour,[44] M. Kowalski,[45] S. Kox,[34] G. Koyithatta Meethaleveedu,[48] J. Kral,[37] I. Králik,[41] F. Kramer,[33] I. Kraus,[26] T. Krawutschke,[27,111] M. Krelina,[2] M. Kretz,[21] M. Krivda,[44,41] F. Krizek,[37] M. Krus,[2] E. Kryshen,[52] M. Krzewicki,[26] Y. Kucheriaev,[15] T. Kugathasan,[6] C. Kuhn,[49] P.G. Kuijer,[57] I. Kulakov,[33] J. Kumar,[48] P. Kurashvili,[92] A. Kurepin,[95] A.B. Kurepin,[95] A. Kuryakin,[70] S. Kushpil,[3] V. Kushpil,[3] H. Kvaerno,[94] M.J. Kweon,[27] Y. Kwon,[79] P. Ladrón de Guevara,[88] I. Lakomov,[66] R. Langoy,[23] S.L. La Pointe,[58] C. Lara,[60] A. Lardeux,[32] P. La Rocca,[43] C. Lazzeroni,[44] R. Lea,[74] Y. Le Bornec,[66] M. Lechman,[6] K.S. Lee,[13] G.R. Lee,[44] S.C. Lee,[13] F. Lefèvre,[32] J. Lehnert,[33] L. Leistam,[6] V. Lenti,[91] H. León,[9] M. Leoncino,[16] I. León Monzón,[99] H. León Vargas,[33] P. Lévai,[7] J. Lien,[23] R. Lietava,[44] S. Lindal,[94] V. Lindenstruth,[21] C. Lippmann,[26,6] M.A. Lisa,[29] L. Liu,[23] V.R. Loggins,[64] V. Loginov,[61] S. Lohn,[6] D. Lohner,[27] C. Loizides,[67] K.K. Loo,[37] X. Lopez,[39] E. López Torres,[78] G. Løvhøiden,[94] X.-G. Lu,[27] P. Luettig,[33] M. Lunardon,[56] J. Luo,[72] G. Luparello,[58] L. Luquin,[32] C. Luzzi,[6] R. Ma,[4] K. Ma,[72] D.M. Madagodahettige-Don,[50] A. Maevskaya,[95] M. Mager,[106,6] D.P. Mahapatra,[42] A. Maire,[27] M. Malaev,[52] I. Maldonado Cervantes,[88] L. Malinina,[46,112] D. Mal'Kevich,[14] P. Malzacher,[26] A. Mamonov,[70] L. Manceau,[16] L. Mangotra,[53] V. Manko,[15] F. Manso,[39] V. Manzari,[91] Y. Mao,[72] M. Marchisone,[39,51] J. Mareš,[113] G.V. Margagliotti,[74,96] A. Margotti,[17] A. Marín,[26] C.A. Marin Tobon,[6] C. Markert,[110] I. Martashvili,[114] P. Martinengo,[6] M.I. Martínez,[87] A. Martínez Davalos,[9] G. Martínez García,[32] Y. Martynov,[19] A. Mas,[32] S. Masciocchi,[26] M. Masera,[51] A. Masoni,[85] L. Massacrier,[32] A. Mastroserio,[22] Z.L. Matthews,[44] A. Matyja,[45,32] C. Mayer,[45] J. Mazer,[114] M.A. Mazzoni,[93] F. Meddi,[115] A. Menchaca-Rocha,[9] J. Mercado Pérez,[27] M. Meres,[69] Y. Miake,[54] L. Milano,[51] J. Milosevic,[94,112] A. Mischke,[58] A.N. Mishra,[100] D. Miśkowiec,[26,6] C. Mitu,[89] J. Mlynarz,[64] B. Mohanty,[10] L. Molnar,[7,6] L. Montaño Zetina,[75] M. Monteno,[16] E. Montes,[59] T. Moon,[79] M. Morando,[56] D.A. Moreira De Godoy,[76] S. Moretto,[56] A. Morsch,[6] V. Muccifora,[55] E. Mudnic,[101] S. Muhuri,[10] M. Mukherjee,[10] H. Müller,[6] M.G. Munhoz,[76] L. Musa,[6] A. Musso,[16] B.K. Nandi,[48] R. Nania,[17] E. Nappi,[91] C. Nattrass,[114] N.P. Naumov,[70] S. Navin,[44] T.K. Nayak,[10] S. Nazarenko,[70] G. Nazarov,[70] A. Nedosekin,[14] M.Niculescu,[89,6] B.S. Nielsen,[47] T. Niida,[54] S. Nikolaev,[15] V. Nikolic,[30] V. Nikulin,[52] S. Nikulin,[15] B.S. Nilsen,[80] M.S. Nilsson,[94] F. Noferini,[17,18] P. Nomokonov,[46] G. Nooren,[58] N. Novitzky,[37] A. Nyanin,[15] A. Nyatha,[48] C. Nygaard,[47] J. Nystrand,[23] A. Ochirov,[24] H. Oeschler,[106,6] S.K. Oh,[13] S. Oh,[4] J. Oleniacz,[98] C. Oppedisano,[16] A. Ortiz Velasquez,[83,88] G. Ortona,[51] A. Oskarsson,[83] P. Ostrowski,[98] J. Otwinowski,[26] K. Oyama,[27] K. Ozawa,[103] Y. Pachmayer,[27] M. Pachr,[2] F. Padilla,[51] P. Pagano,[90] G. Paić,[88] F. Painke,[21] C. Pajares,[35] S.K. 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We report the first measurement of the net–charge fluctuations in Pb–Pb collisions at $\sqrt{s_{\rm NN}} =$ 2.76 TeV, measured with the ALICE detector at the CERN Large Hadron Collider. The dynamical fluctuations per unit entropy are observed to decrease when going from peripheral to central collisions. An additional reduction in the amount of fluctuations is seen in comparison to the results from lower energies. We examine the dependence of fluctuations on the pseudo–rapidity interval, which may account for the dilution of fluctuations during the evolution of the system. We find that the ALICE data points are between the theoretically predicted values for a hadron gas and a Quark–Gluon Plasma.

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The ALICE experiment [1] at the Large Hadron Collider (LHC) is a multi–purpose detector designed to study the formation and evolution of nuclear matter at high temperatures and energy densities. One of the major goals of the experiment is to explore as many signals as possible towards characterizing the properties of the Quark–Gluon Plasma (QGP), the deconfined state of quarks and gluons, produced in high energy heavy–ion collisions. The study of event–by–event fluctuations provides a powerful tool to characterize the thermodynamic properties of the system. The fluctuations of conserved quantities, like net–charge of the system, are predicted to be one of the most sensitive signals of the QGP formation and phase transition, and may provide complementary understanding of strong interactions [2–9].

In the QGP phase, the charge carriers are quarks with fractional charges, whereas the particles in a hadron gas (HG) carry unit charge. The fluctuations in the net–charge depend on the squares of the charge states present in the system. Consequently, the net–charge fluctuations in the QGP phase are significantly smaller compared to that of a HG [2]. At the same time, if the initial QGP phase is strongly gluon dominated, the fluctuation per entropy may further be reduced as the hadronization of gluons increases the entropy [3]. Thus the net–charge fluctuations are strongly dependent on which phase they originate from. However, the net–charge fluctuations may get affected by uncertainties arising from volume fluctuations, so one considers the fluctuations of the ratio, $R = N_+/N_-$. Here N_+ and N_- are the numbers of positive and negative particles respectively, measured in a specific transverse momentum ($p_{\rm T}$) and pseudo–rapidity (η) window. The parameter R is related to the fluctuations of the net–charge via the D–measure as per the following expression [2, 4, 5]:

$$D = \langle N_{\rm ch}\rangle\langle\delta R^2\rangle \approx 4\frac{\langle\delta Q^2\rangle}{\langle N_{\rm ch}\rangle}, \tag{1}$$

which provides a measure of the charge fluctuations per unit entropy. Here the $\langle ...\rangle$ denotes an average of the quantity over an ensemble of events. The term $\langle\delta Q^2\rangle$ is the variance of net charge, $Q = N_+ - N_-$ and $N_{\rm ch} = N_+ + N_-$. The D–measure has been estimated for several different theoretical considerations including those of the lattice calculations. In a simple picture by neglecting quark–quark interactions, D is found to be approximately 4 times smaller for a QGP compared to a HG [2]. Lattice calculations which include the quark–quark interactions give a quantitatively different estimate for a QGP phase, still significantly smaller than for a HG. It has been shown that $D = 4$ for an uncorrelated pion gas, and after taking resonance yields into account, the value decreases to $D \simeq 3$. For a QGP, D is significantly lower and has been calculated to be $D \simeq 1.0$–1.5 where the uncertainty arises from the uncertainty of relating the entropy to the number of charged particles in the final state [5]. Thus, a measurement of D can be effectively used as a probe for distinguishing the two phases, the HG and the QGP. However in reality, these fluctuations may get diluted in the rapidly expanding medium due to diffusion of particles in rapidity space [8, 9]. Several other effects, such as collision dynamics, radial flow and final state interactions may also affect the amount of measured fluctuations [2, 10, 11].

In the experiment, the net–charge fluctuations are best studied [11–16] by calculating the quantity $\nu_{(+-,{\rm dyn})}$ defined as:

$$\nu_{(+-,{\rm dyn})} = \frac{\langle N_+(N_+-1)\rangle}{\langle N_+\rangle^2} + \frac{\langle N_-(N_--1)\rangle}{\langle N_-\rangle^2} - 2\frac{\langle N_-N_+\rangle}{\langle N_-\rangle\langle N_+\rangle}, \tag{2}$$

which is a measure of the relative correlation strength of particle pairs. A negative value of $\nu_{(+-,{\rm dyn})}$ signifies the dominant contribution from correlations between pairs of opposite charges. On the other hand, a positive value indicates the significance of the same charge pair correlations. The $\nu_{(+-,{\rm dyn})}$ has been found to be robust against random efficiency losses [16–18]. D–measure and $\nu_{(+-,{\rm dyn})}$ are related to each other by [5]:

$$\langle N_{\rm ch}\rangle\nu_{(+-,{\rm dyn})} \approx D - 4. \tag{3}$$

The values of $\nu_{(+-,{\rm dyn})}$ need to be corrected for global charge conservation [16]. The predictions for the D–measure are based on the assumption of vanishing net–charge in the system. However, in a realistic situation, the system under consideration has a small but finite net–charge. A correction due to finite net–charge effect also needs to be applied [4].

In this letter, we report the first measurements of net–charge fluctuations, by calculating $\nu_{(+-,{\rm dyn})}$ and the D–measure, as a function of collision centrality in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV at the LHC with the ALICE detector. We also make a comparison of the experimental results to the theoretical predictions.

Details of the ALICE experiment and its detectors can be found in [1]. For this analysis, we have used the Time Projection Chamber (TPC) [19] to reconstruct charged particle tracks. The detector provides a uniform acceptance with an almost constant tracking efficiency of about 80% in the analyzed phase space ($|\eta| < 0.8$ and 0.2 GeV/c $< p_{\rm T} < 5$ GeV/c). The interaction vertex was measured using the Silicon Pixel Detector (SPD), the innermost detector of the Inner Tracking System (ITS) of ALICE. In the analysis, we have considered events with a vertex $|v_{\rm z}| < 10$ cm to ensure a uniform acceptance in the central pseudo–rapidity region. The minimum bias trigger of ALICE consisted of a coincidence of at least one hit on each of the two VZERO scintillator detectors, positioned on both sides of the interaction point, while at the startup of data taking period an additional requirement of having a coincidence with a signal from the SPD was also introduced. The background events coming from parasitic beam interactions are removed by a standard offline event

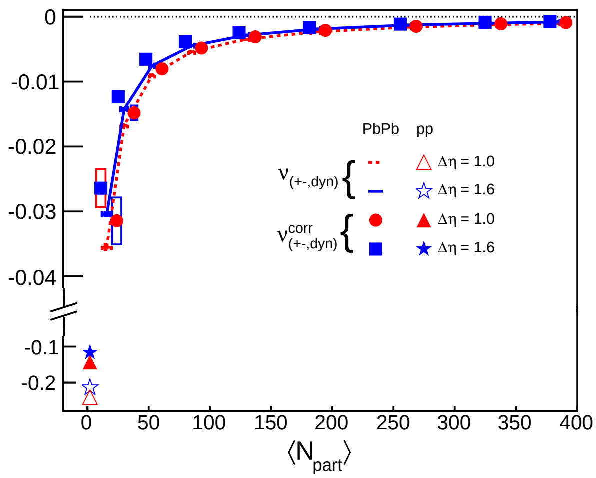

FIG. 1. Dynamical net–charge fluctuations, $\nu_{(+-,\mathrm{dyn})}$ and their corrected values, $\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$, for charged particles produced in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV as a function of centrality expressed in terms of the number of participating nucleons. $\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ points are shifted along x-axis for better representation. Superimposed are the results for pp collisions at $\sqrt{s} = 2.76$ TeV. The results are shown for two different $\Delta\eta$ windows. The statistical (bar) and systematic (box) errors are plotted.

selection procedure, which requires the VZERO timing information and hits in the SPD.

We present the results as a function of centrality that reflects the collision geometry. The collision centrality is determined by cuts on the VZERO multiplicity as described in [20]. A study based on Glauber model fits [21–23] to the multiplicity distribution in the region corresponding to 90% of the most central collisions, where the vertex reconstruction is fully efficient, facilitates the determination of the cross section percentile and the number of participants. The resolution in centrality is found to be $< 0.5\%$ RMS for the most central (0-5%) collisions, increasing towards 2% RMS for peripheral (70-80%) collisions [20].

We require tracks in the TPC to have at least 80 reconstructed space points with a χ^2 per TPC cluster of the momentum fit less than 4. We reject tracks with distance of closest approach (*dca*) to the vertex larger than 3 cm both in the transverse plane and in the longitudinal direction. We have performed an alternative analysis with tracks reconstructed using the combined tracking of ITS and TPC. In this case, the *dca* cuts were 0.3 cm in the transverse plane as well as in the longitudinal direction. The results obtained with both tracking approaches are in agreement.

The data analysis has been performed for Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV and pp collisions at the same centre–of–mass energy. An identical analysis procedure has been followed for both Pb–Pb and pp data. We calculate the $\nu_{(+-,\mathrm{dyn})}$ from the experimental measurements of positive and negative charged particles counted in $\Delta\eta$ windows, defined around mid–rapidity (for example, $\Delta\eta = 1$ corresponds to $-0.5 \leq \eta \leq 0.5$) and in the p_{T} range from 0.2 to 5.0 GeV/c. In Figure 1, we present the $\nu_{(+-,\mathrm{dyn})}$ as a function of centrality, expressed in terms of the number of participating nucleons. Moving from left to right along the x–axis of the figure corresponds to moving from peripheral to central collisions. The results are presented for $\Delta\eta = 1$ and 1.6, for both Pb–Pb and pp collisions. In all cases, the magnitude of $\nu_{(+-,\mathrm{dyn})}$ is observed to be negative, indicating the dominance of the correlation term in Eq. 2. The absolute values of $\nu_{(+-,\mathrm{dyn})}$ for pp collisions are larger compared to those measured for Pb–Pb collisions. When going from peripheral to central events, the absolute values of $\nu_{(+-,\mathrm{dyn})}$ are seen to decrease monotonically.

The values of $\nu_{(+-,\mathrm{dyn})}$ have to be corrected for global charge conservation and finite acceptance [16]. If all charges are accepted, the global charge conservation would lead to vanishing fluctuations. This will yield the minimum value of $\nu_{(+-,\mathrm{dyn})}$ to be -4/$\langle N_{\mathrm{total}}\rangle$, where $\langle N_{\mathrm{total}}\rangle$ is the average total number of charged particles multiplicity produced over full phase space. The corrected value of $\nu_{(+-,\mathrm{dyn})}$ is then:

$$\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})} = \nu_{(+-,\mathrm{dyn})} + \frac{4}{\langle N_{\mathrm{total}}\rangle}. \quad (4)$$

Since the value of $\langle N_{\mathrm{total}}\rangle$, has not been reported by experiments, we have obtained these values from HIJING [24] and PYTHIA [25] event generators for Pb–Pb and pp collisions, respectively. The corrected values, $\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$, are calculated and plotted in Figure 1 as a function of the number of participating nucleons for Pb–Pb as well as pp collisions. The absolute values of $\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$are smaller compared to $\nu_{(+-,\mathrm{dyn})}$in all cases. The differences are more apparent for pp and peripheral Pb–Pb collisions than for central collisions.

The calculations of the D–measure were consequently done starting from the corrected values of $\nu_{(+-,\mathrm{dyn})}$ in Eq. 3. A systematic check of correcting the D–measure has been performed by using $D \to D/(C_\mu C_\eta)$, where $C_\mu = \frac{\langle N_+\rangle^2}{\langle N_-\rangle^2}$ and $C_\eta = 1 - \frac{\langle N_{\mathrm{ch}}\rangle^2}{\langle N_{\mathrm{total}}\rangle}$ [4]. A difference of 3–7% (depending on the $\Delta\eta$ window) has been included as one of the systematic errors to D. For the rest of the manuscript the corrected values of $\nu_{(+-,\mathrm{dyn})}$ and D are presented.

The systematic uncertainties have additional contributions from the following sources: (a) uncertainty in the determination of the interaction vertex, (b) different magnetic field polarities, (c) contamination from secondary tracks (*dca* cuts), (d) centrality definition using different detectors, (e) selection criteria at the track level, and (f) different tracking scenarios. The total systematic error on $\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ amounts to 6–10% in going from peripheral to central collisions. The error on the product of

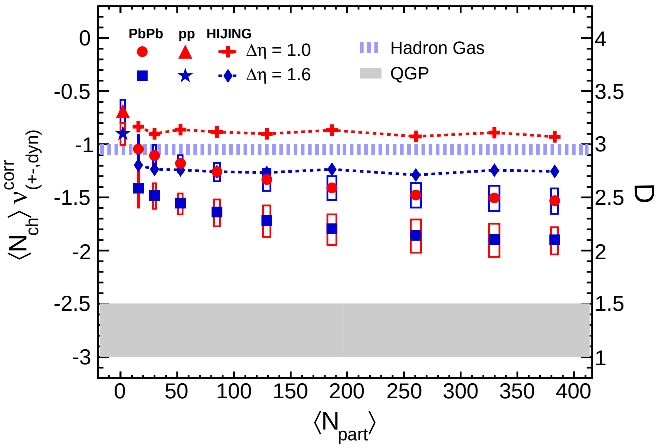

FIG. 2. $\langle N_{\rm ch}\rangle\nu^{\rm corr}_{(+-,{\rm dyn})}$ (left axis) and D (right axis) as a function of the number of participants for $\Delta\eta = 1$ and 1.6 in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV and pp collisions at $\sqrt{s} = 2.76$ TeV. Also shown are results from the HIJING event generator for both the $\Delta\eta$ windows. Both statistical (error bar) and systematic (box) errors are shown.

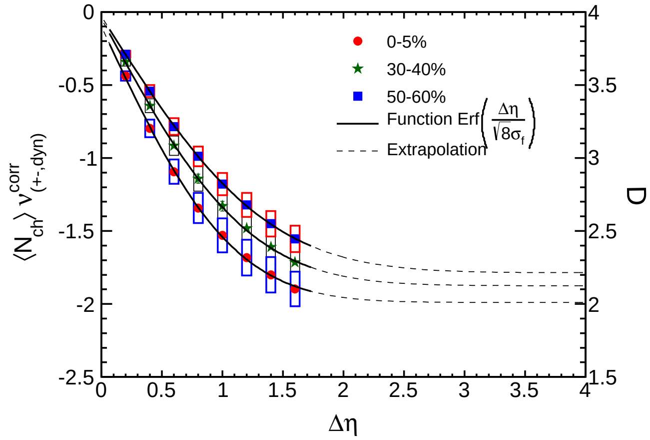

FIG. 3. $\langle N_{\rm ch}\rangle\nu^{\rm corr}_{(+-,{\rm dyn})}$ (left axis) and D (right axis) as a function of $\Delta\eta$ window for three different centrality bins in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. The data points are fitted with the functional form, ${\rm erf}(\Delta\eta/\sqrt{8}\sigma_{\rm f})$. The dashed lines correspond to the extrapolation of the fitted curves. Both statistical (error bar) and systematic (box) errors are shown.

number of charged particles and $\nu^{\rm corr}_{(+-,{\rm dyn})}$ remains within 7–13% at all centralities. The systematic and statistical uncertainties in all the figures are represented by boxes and error bars, respectively. The statistical errors are small and within the sizes of the symbols in most cases.

Figure 2 presents the values of $\langle N_{\rm ch}\rangle\nu^{\rm corr}_{(+-,{\rm dyn})}$and D in the left and right axes, respectively, as a function of the number of participating nucleons. The $\langle N_{\rm ch}\rangle$ values have been measured for different centralities and $\Delta\eta$ windows, and corrected for detector inefficiencies [20]. Both the results from the Pb–Pb and pp analyses are shown. The shaded bands in the figure indicate the predictions for a HG and a QGP. The figure also shows the results from the HIJING event generator for $\Delta\eta = 1$ and 1.6, which are observed to be close to the HG line and at the same time independent of centrality. The pp results for $\Delta\eta = 1.6$ agrees very well with the HG prediction. The experimental results for Pb–Pb for both the $\Delta\eta$ windows are observed to be below the HG predictions and above those of the QGP. The values of D for $\Delta\eta = 1.6$ are lower compared to those for $\Delta\eta = 1$ for all centralities.

A decreasing trend of D has been observed while going from peripheral to central collisions, as seen in Figure 2. This centrality dependence may arise partly because of the presence of radial flow [10]. The radial flow velocity could lead to the kinetic focussing of the produced particles, causing a narrowing of the opening angles. Therefore, it is expected that the number of positive and negative particles may get redistributed in a finite phase space. This may affect the magnitude of net–charge fluctuations. The effect of radial flow on $\nu_{(+-,{\rm dyn})}$ has been estimated by using two different methods. First, we have used an afterburner [26] on the HIJING events where the particles get a boost in the transverse momenta because of the radial flow velocity. The magnitudes of $\nu_{(+-,{\rm dyn})}$ and D are observed to be close to each other for both HIJING and HIJING with the afterburner. In the second method, D is calculated using the AMPT model [27]. Both versions of this generator, the string melting and the default, were studied. The observed centrality dependence in the data are not seen with the AMPT model. These studies indicate that the presence of radial flow may not be responsible for the centrality dependence of the D–measure.

The measured fluctuations may get diluted during the evolution of the system from hadronization to kinetic freeze-out because of the diffusion of charged hadrons in rapidity. In ref. [8, 9], this has been addressed where a diffusion equation has been proposed to study the rapidity dependence of net–charge fluctuations. It has been conjectured that, taking the dissipation into account, the asymptotic value of fluctuations may be close to the primordial fluctuations in large rapidity windows corresponding to the hadronization stage. This has been explored for the ALICE data points by plotting $\langle N_{\rm ch}\rangle\nu^{\rm corr}_{(+-,{\rm dyn})}$ and D as a function of $\Delta\eta$ for three centrality bins, as shown in Figure 3. We observe that for a given centrality bin, the D–measure shows a strong decreasing trend with the increase of $\Delta\eta$. In fact, the curvature of D has a decreasing slope with a flattening tendency at large $\Delta\eta$ windows. Following the prescriptions of [8, 9], we fit the data points with the functional form, ${\rm erf}(\Delta\eta/\sqrt{8}\sigma_{\rm f})$, which represents the diffusion in rapidity space. Here, $\sigma_{\rm f}$ characterizes the diffusion at freeze–out.

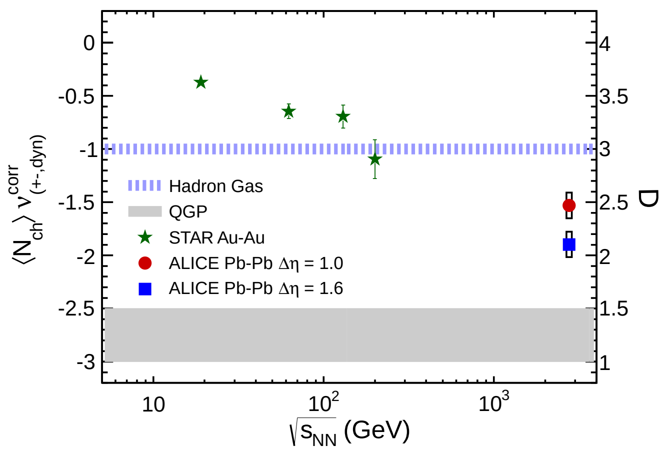

FIG. 4. Energy dependence of the net–charge fluctuations, measured in terms of $\langle N_{\mathrm{ch}}\rangle\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ (left axis) and D (right axis), for the top central collisions. The results from the STAR [11] and ALICE experiments are presented for $\Delta\eta = 1$ after the correction for charge conservation. The ALICE results are further extrapolated to obtain the asymptotic value, shown by the solid red circle. Both statistical (error bar) and systematic (box) errors are shown.

The resulting values of σ_{f} are 0.42 ± 0.04, 0.48 ± 0.06 and 0.53 ± 0.05 for the 0-5%, 30-40% and 50-60% centralities, respectively. The fitted curves are shown as solid lines in Figure 3. The dashed lines are extrapolations of the fitted curves to higher $\Delta\eta$, which yield the asymptotic values of D. For the top 5% centrality, the measured values of D are $2.47\pm0.01(\mathrm{stat.})\pm0.13(\mathrm{sys.})$ for $\Delta\eta = 1$ and $2.10\pm0.02(\mathrm{stat.})\pm0.12(\mathrm{sys.})$ for $\Delta\eta = 1.6$. The extrapolated value of D is $1.99\pm0.09(\mathrm{stat.})\pm0.17(\mathrm{sys.})$.

The evolution of the net–charge fluctuations with beam energy can be studied by combining the ALICE data for Pb–Pb collisions with those of the STAR experiment [11] for Au–Au collisions at four RHIC energies. In Figure 4, we present the values of $\langle N_{\mathrm{ch}}\rangle\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ (left axis) and D (right axis) for the top central collisions from ALICE at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV and for STAR, Au–Au collisions at four different energies. The ALICE data points correspond to $\Delta\eta = 1$ and 1.6, whereas for STAR the values for $\Delta\eta = 1$ are shown. For the STAR data, $(dN_{\mathrm{ch}}/d\eta)\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ is plotted instead of $\langle N_{\mathrm{ch}}\rangle\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$, where $dN_{\mathrm{ch}}/d\eta$ is approximately equal to $\langle N_{\mathrm{ch}}\rangle$ for $\Delta\eta = 1$ at central rapidity. The theoretical predictions for a hadron gas and a QGP are also indicated in the figure.

In Figure 4, we observe a monotonic decrease in the magnitude of the net–charge fluctuations with increasing beam energy. For the top RHIC energy of $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, the measured data of STAR is close to the prediction for a hadron gas. Below this energy, the data points are above the hadron gas value. We note that the STAR results are obtained for $\Delta\eta = 1$ where the fluctuations may still be significantly affected by diffusion. At 2.76 TeV, we observe that the values of D for both the $\Delta\eta$ windows are within the predictions for a hadron gas and a QGP. At $\Delta\eta = 1.6$ the value of D is closer to that of the QGP prediction.

In summary, we have presented the first measurements of dynamic net–charge fluctuations at the LHC in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV in terms of $\nu_{(+-,\mathrm{dyn})}$, and their corrected values, $\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ (corrected for charge conservation and finite acceptance effect). The results for pp collisions at the same center–of–mass energy are found to be in agreement with hadron gas prediction. The values of $\nu_{(+-,\mathrm{dyn})}$ and $\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$are seen to be negative in all cases, indicating the dominance of the correlation of positive and negative charges. A decrease in fluctuations is observed while going from peripheral to central collisions. The D–measure, which gives the charge fluctuations per entropy, is calculated from $\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ and from the measured average charged particle multiplicity. A decreasing trend of D is observed in going from peripheral to central collisions. Model studies indicate that the presence of radial flow may not be the cause of this decrease. The dissipation of signal during the evolution of the fireball from the hadronization to freeze-out has been estimated by fitting D as a function of the $\Delta\eta$ window. The extrapolation of the fit function yields the asymptotic value of D, which is not very different from the measurement at $\Delta\eta = 1.6$. The beam energy dependence of charge fluctuations has been studied by comparing the ALICE data with those from the STAR experiment at RHIC for Au–Au collisions at four energies. A monotonic decrease in the value of D, measured at $\Delta\eta = 1$, has been observed. The STAR data points at RHIC top energy are close to the prediction for a hadron gas. This may be due to the fact that the fluctuation may be not strong enough to be measured or because of the dilution of fluctuation during the evolution process. The ALICE data points are below the prediction for a hadron gas and above that of the QGP. Moreover, these data points show an additional decrease of D at $\Delta\eta = 1.6$. For the top central collisions, the measured value of D turns out to be $2.10\pm0.02(\mathrm{stat.})\pm0.12(\mathrm{sys.})$ which is to be compared with theoretical predictions.

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